The Relationship Between Ground Data Systems and Flight Operations for the Aura Project TES Instrument

Steven R. Tyler and Padma Varanasi
Jet Propulsion Laboratory
4800 Oak Grove Drive
Pasadena, CA 91109
818-393-0669 and 818-354-5000
steven.r.tyler@jpl.nasa.gov and padma@jord.jpl.nasa.gov

Abstract - While Ground Data systems are normally thought of primarily in terms of processors of Science and Calibration data, they are also used by Instrument Operations teams specifically. This paper briefly outlines Aura's Tropospheric Emission Spectrometer (TES) experiment and TES Instrument Operations activities. It describes the data routed to TES Operations personnel by the Ground Data system, which are used to trend the health, status, and performance of the TES instrument. TES is atypical in that it has some engineering data that are available only in the high rate data stream, rather than in low-rate engineering data as well.

Blocks of commands to perform anticipated TES tasks were developed in parallel with TES flight software design. This paper concludes by showing how this early development of command blocks permitted significantly more flexibility in resolving a variety of TES Operations issues.

TABLE OF CONTENTS

1. INTRODUCTION: TES INSTRUMENT AND EXPERIMENT

The TES Instrument, managed and built at the Jet Propulsion Laboratory (JPL), is one of a suite of four instruments on the EOS Aura spacecraft. Aura is funded by NASA and managed and operated by the Goddard Space Flight Center (GSFC). The spacecraft is being developed at TRW, and is scheduled for launch from Vandenberg Air Force Base in June, 2003. EOS Aura is an Earth Observing Satellite (EOS) which will study atmospheric chemistry from a 705-km altitude polar orbit. The other three instruments on Aura are the High Resolution Dynamics Limb Sounder (HiRDLS), the Microwave Limb Sounder (MLS) and the Ozone Monitoring Instrument (OMI).

The Tropospheric Emission Spectrometer (TES) is an infrared imaging Fourier Transform Spectrometer (FTS) which is intended to measure and profile virtually all infrared-active molecules in the Earth's lower atmosphere. It has a spectral range of 3.3 μm to 15.4 μm, and a resolution of 0.025 cm^{-1}. It operates using both natural thermal emission (4.1 to 15.4 μm) and solar reflection (3.3 to 5.0 μm). An FTS produces interferograms by varying the optical path length of incoming radiation. The spectrum of the incident radiation is proportional to the real part of the Fourier Transform of the interferogram.

The focus of TES is on the global distribution of tropospheric ozone and on the factors that control its concentration, in order to support development and improvement of models of the present and future states of the Earth's lower atmosphere. Accordingly, TES will generate vertical concentration profiles of ozone, methane, water vapor, nitric oxide, nitrogen dioxide, and nitric acid from the surface to the lower stratosphere. It is to provide these measurements for roughly 16 orbits out of every 29, to the extent possible given cloud interference and other physical limitations. In addition, it will determine local atmospheric temperature profiles, surface temperatures, emissivities and reflectances, and measure a large variety of other chemical species that are of sporadic or specialized interest, such as those produced by volcanoes, biomass burning, or industrial accidents.

TES obtains its data in scans of 4-second duration in the nadir direction and 16-second scans while staring at the trailing limb. The nadir observations supply limited vertical resolution but excellent horizontal spatial resolution, while the limb observations provide good vertical resolution and enhanced sensitivity for trace constituents at the expense of having poorer line-of-sight spatial resolution and a higher chance of cloud interference.

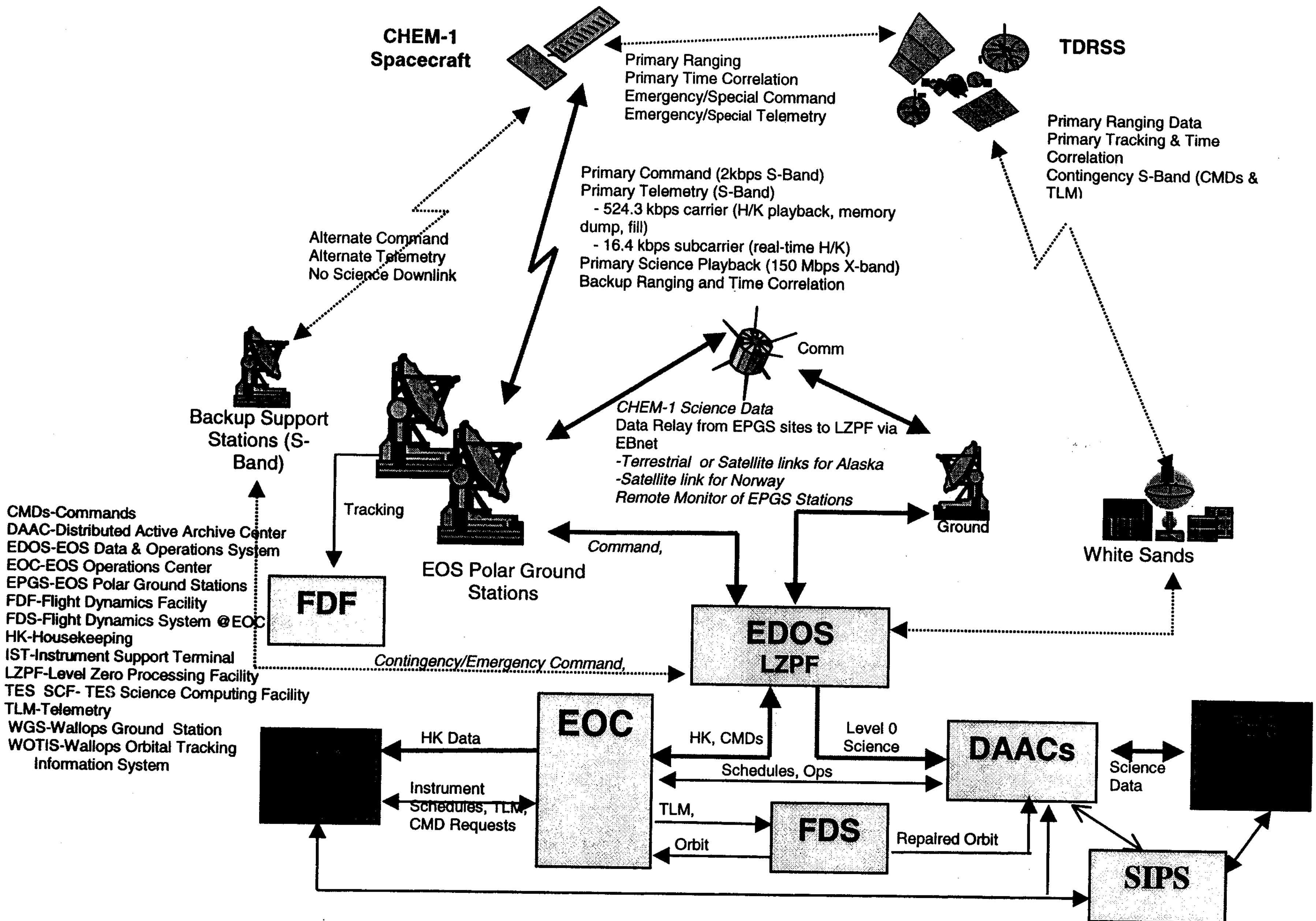

Figure 1. TES Flight Operations Architecture

TES produces up over 350 gigabits (Gb) of raw interferogram data every two days. As Figure one indicates, these data, along with instrument engineering data and other ancillary data, are transmitted back to Earth in spacecraft contact sessions of several minutes apiece, once per orbit, via a 155 Mbps X-band link. The data arrive at ground stations in Alaska and Norway and are then transmitted electronically to the EOS Data and Operations System (EDOS) at GSFC in telemetry packets. These data are then sent to the Distributed Active Archive Center (DAAC) at the Langley Research Center (LaRC) and then to JPL for processing by the TES Scientific Investigator-led Processing System (SIPS), as shown in Figure 1.

2. TES SUBSYSTEMS, COMMANDS, AND CONSTRAINTS

The following is a brief description of the TES subsystems and some of the commands, constraints, and onboard autonomous fault responses associated with them. The constraints are generally made into TES "Flight Rules," which must be followed in TES commanding. A block diagram of TES is shown in Figure 2.

Pointing Control Subsystem (PCS)

The PCS contains a flat mirror, on a ginbaled mount, which points the TES field of view. This mirror entails some operational complexity for TES, since proper articulation depends upon the Aura ephemeris and attitude.

The most frequent PCS command is used to point the PCS gimbal. Depending on a parameter in this command, the PCS mirror can be pointed at the trailing limb, at nadir, at any angle within 45 degrees of nadir, at cold space, at a blackbody calibration target, and at a position where the pitch bearing can be lubricated, as appropriate.

The most significant PCS constraint involves the minimum time necessary to move the gimbal to a new position. If a time is too low, there may be a risk of exciting structural modes of TES or of Aura. If a time is too large, it may preclude taking sufficient Science data. There is also a maximum time constraint between special mirror positionings for bearing lubrication during use. Another constraint is to make sure the PCS mirror is pointed inwards when TES is in a non-data taking "safe" mode, to avoid the possibility of having it illuminated by the Sun.
If a PCS motor current is too high, fault protection will shut down the PCS. The PCS will also be turned off if the ancillary data needed for determining where to point is invalid or missing.

Interferometer Control Subsystem (ICS)

The Interferometer modulates incoming radiation by altering the optical path length between the interferometer's two arms. This is accomplished by moving its retroreflector mirror back and forth along a track between two roof mirrors at a constant velocity via the TES translator mechanism.

The Interferometer Control Subsystem consists of a motor, encoder, and associated electronics and software that control the motion of the translator mechanism.

The motion of the translator from one limit to the other is called a scan. During a translator scan, the radiation is sampled by the TES detectors, and an interferogram is recorded. This is the fundamental data product of the instrument.

A nadir-view scan (a "short scan") takes 4 seconds and a limb-view scan (a "long scan") is 16 seconds. The operational significance of the scans is that they are performed almost continuously during nominal operations and that they need to be synchronized with the motion of the other TES mechanisms. The most frequent ICS commands are to perform a 4-second scan, to perform a 16-second scan, and to reset the translator to its starting point in between all scans.

A very important constraint on the ICS applies at TES activation. The ICS is latched, and this latch must be released prior to opening the TES instrument cover (the "Earthshade") or else the reduction in temperature may cause the ICS latch to become stuck permanently. Another major ICS constraint involves the minimum time between initiating successive scans.

The ICS may be shut down, either autonomously or via ground commands, should an ICS motor current or the position or rate of the translator be out of limits.

Focal Plane Subsystem (FPS)

The FPS images and records the signals from the interferometer. and converts these signals to values that will be downlinked in the high-rate telemetry data stream. The FPS includes imaging optics, filter wheels, the four detector arrays and their corresponding amplifiers, and signal chains.

The main commands associated with the FPS are to reposition and heat the filter wheel mechanisms, to change the gain settings for the signal chains, and to control the sampling interval. The first two of these commands are required almost every time a scan is performed, and must be synchronized with commands to the other mechanisms.

Constraints on the FPS include the minimum times between commands, the minimum time needed to move the filter wheels to new positions, the maximum time between wheel mechanism heatings during use, and a restriction to avoid moving or changing the temperature of a wheel during data-taking.

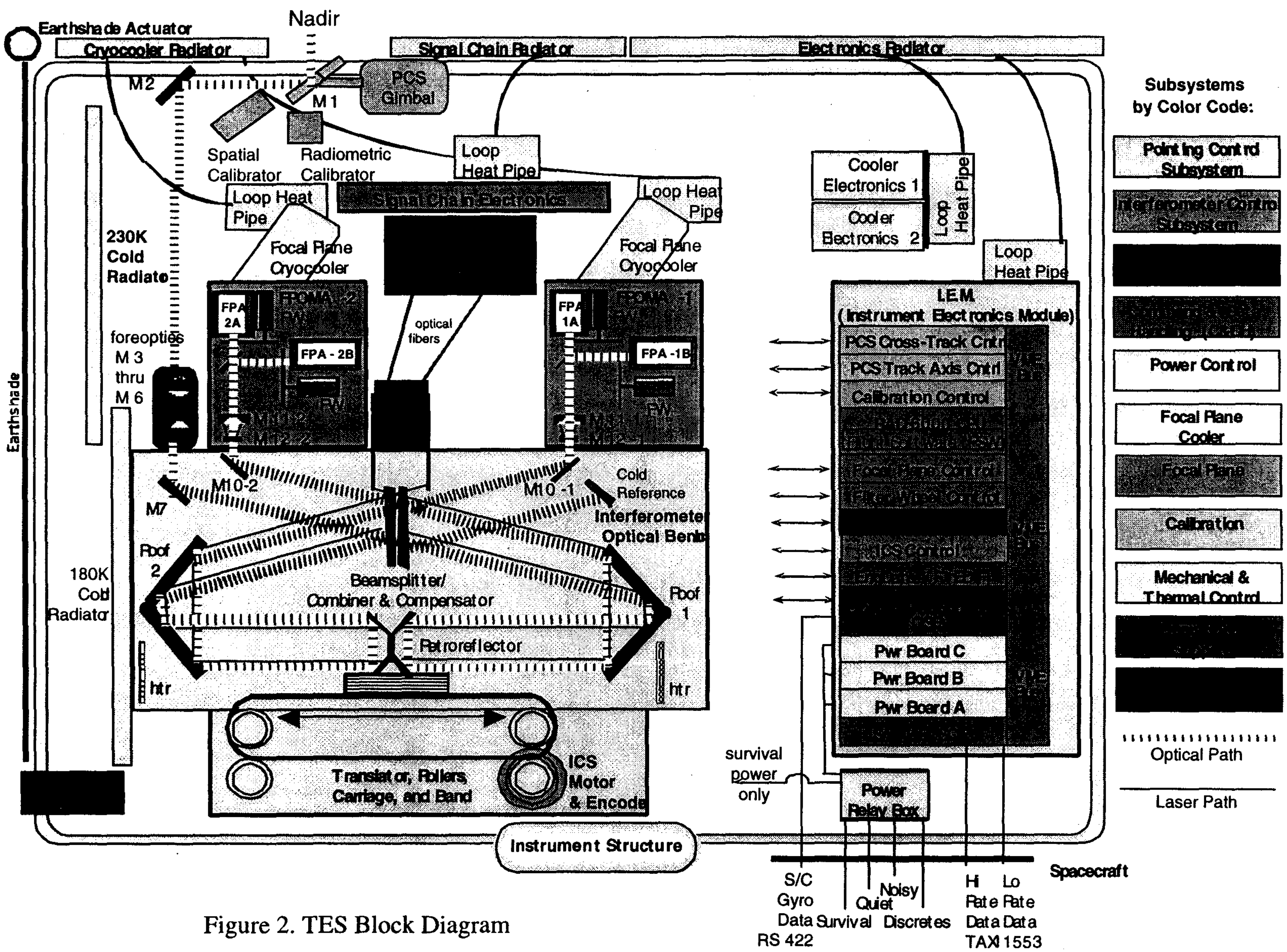

Figure 2. TES Block Diagram

If a Focal Plane Assembly becomes too hot, a Fault Protection response will turn off heaters. Should the filter wheel mechanisms become too cold, Fault Protection may be used to heat them.

Power Subsystem

The Power Subsystem is the interface between the instrument electronics and the spacecraft power buses. These buses accept a total of over 320 watts of 29-volt DC power from the Aura spacecraft. The three TES buses are called the quiet bus, the noisy bus, and the survival bus, with the noisy bus being used for a higher maximum rate of change of current than the quiet bus.

The main command to the Power Subsytem is to set the noisy bus relays. During activation, the quiet bus needs to be turned on before the noisy bus so that it can reconfigure these relays. Other constraints on the Power subsystem involve the closing of relays for decontamination heaters.

There is a possibility of a TES bus undervoltage, and this may trigger a Fault Protection response. In addition, Aura has a "Survival" Mode in which the spacecraft would be slowly rotated and power to TES would be reduced to 100 watts over the survival bus only. TES is essentially off during survival mode, with the survival bus power driving passive, uncommandable heaters only.

Command and Data Handling Subsystem (C&DH)

The C&DH subsystem accepts commands through the spacecraft and controls TES subsystem operations. It collects housekeeping data from the instrument and spacecraft ancillary and gyro data. In addition, it formats and controls data flow.

The C&DH subsytem includes the TES Flight Computer, a 20 MIPS RISC processor with 128 Mbytes of RAM, 3 Mbytes of EEPROM, and a VME interface to the instrument communication and control bus. It has a high rate data buffer and formatter which puts all Science data into 8192-byte CCSDS telemetry packets, and an engineering interface board which collects subsystem voltage and temperature data.

There are a large number of C&DH commands. Several of these are control commands to be used within macros (stored blocks of timed commands that are stored on the spacecraft and executed by calling them). These include commands to call other macros and to loop. Some commands permit accessing a parameter table that supplies filter wheel positions, signal chain gains, and PCS pointing. There are also commands to load or to dump memory, macros, or tables.

C&DH commands also are used to keep track of TES status and to monitor bit errors.

Constraints on the C&DH may include a maximum number of write operations to a given EEPROM location and restrictions on the initial state of VME registers.

Mechanical Subsystem

The Mechanical Subsystem provides a stable thermal and structural environment for the other instrument subsystems as well as mechanical interfaces to the TES platform. It includes heaters, insulation blankets, and an Earth shade. The Earth shade protects space-viewing cold radiators from incident Earth albedo and Aura spacecraft radiation during nominal spacecraft operations.

Commands to the Mechanical Subsystem include those to release the Earth shade, to operate the decontamination heaters, and to control the optical bench operational heater. A constraint on the Mechanical Subsystem is to keep the temperature of the optical bench lower than that of the focal planes during decontamination.

Laser Subsystem

The Laser Subsystem provides sampling signals that measure the change in the optical path difference between the two arms of the interferometer. The signals are transmitted to the Focal Plane electronics to control detector sampling.

The laser is a diode-pumped Nd:YAG, with a wavelength of 1.064 μm, which is then the optical path spacing at which samples are taken. There are two redundant lasers.

Commands to the Laser Subsystem are to switch power on to a laser, to switch on current to a laser diode, to set a diode current, to set a crystal temperature, and to set a laser electronics detector gain. Constraints include a restriction against operating both lasers at once, and a minimum warm-up time between powering on a laser and switching current to the diode.

Focal Plane Cooler Subsystem

The four TES detector arrays are arranged in two pairs, with each pair mounted in an independent housing. Each housing is coupled to a dedicated mechanical cryocooler. These coolers are utilized simultaneously during TES operations and provide a stable 65 K environment for the detectors and pre-amplifiers.

There are a large number of Focal Plane Cooler commands, but they are represented as parameters of a single TES command. The coolers are supposed to be on during nominal operations, so the operational complexity comes at activation. At this time, a number of sets of commands must be sent and verified, one at a time. These are to close the cooler electronics relays, upload a software patch for cryocooler operation, upload trip level and enable parameters for the cryocoolers, change cooler mode to "normal," and activate the cryocoolers.

Constraints on the Cryocoolers include restrictions against having one on and the other off for an extended period, spacing of consecutive commands to a single cooler, minimum time between cooler A and cooler B startups, and minimum spacing between startup commands and further commands. A cryocooler overtemperature will provoke a Fault Protection response.

Calibration Subsystem

The TES calibration subsystem includes a Radiometric Calibration Source (RCS), a spatial calibration source, and their electronics.

The RCS is a variable-temperature, radiometrically-calibrated blackbody source. It overfills the TES field-of-view, and enables TES to relate its spectro-radiometric response to a known input signal while in orbit. The temperature of the source can be allowed to cool to roughly the ambient temperature and then raised by heaters to its nominal value of 340 K. This permits monitoring of any non-linearities in the TES instrument response.

The spatial calibration source provides an infrared image of a line source. By discrete movements of the PCS gimbal mirror, the image of this source is stepped across the detectors. The response of each detector element, as the image is stepped across it, is used to determine the relative alignment of each pixel, and thus to verify the relative alignment of each of the four TES detectors. It is anticipated that spatial calibrations will be performed once or twice per year (possibly more frequently early in the mission).

Commands for the Calibration Subsystem permit selecting a platinum resistance thermometer, selecting an RCS heater, turning the RCS or spatial source on or off, setting the RCS temperature, and setting the spatial calibration source contrast. Constraints include times allotted for cooldown or heating of the RCS, a restriction against setting the RCS temperature above 350 K, a maximum spatial calibration source contrast setting, and a requirement that both the RCS and spatial sources be on during decontaminations. An RCS overtemperature will trigger a Fault response.

3. TES OBSERVATIONS

TES Global Survey

The Global Survey is the only TES standard product science activity. Including two orbits of pre-calibration, it runs for 18 orbits out of every 29 (actually there is one extra non-survey orbit every 16 days, so the Global Survey runs for 144 orbits out of 233). A TES global survey sequence consists of seven scans: one 4-second view of cold space, one 4-second view of the RCS blackbody, two 4-second nadir views, and three long scan limb views of 16 seconds each. The total duration of an individual global survey is 81.2 seconds. There are 73 global survey sequences in each orbit. Alternate global survey sequences make use of different filter sets.

The Global Survey macros are triggered at the South Pole Apex crossing The average data rate is 3.7 Mbps. The 18-orbit activities generate 382 Gb of data.

The Global Survey places a relatively high duty cycle on several TES mechanisms. During each 81.2-second sequence, there are several commands to move the translator, the gimbal, and two of the four filter wheels. The translator is in almost constant motion, with 64 of the 81.2 seconds spent taking data, 5.6 seconds starting up prior to its seven scans and stopping after them, and 8 seconds in two resets between short and long scans. This is more than a 95% duty cycle for the translator, which is commanded nine times in each sequence. The PCS gimbal is commanded five times per sequence, and spends 14 seconds in motion, which is about a 17% duty cycle. The filter wheels are commanded four times, and required to move in 0.7 seconds, so that they can complete their motion between successive scans. This imposes less than a 3.5% duty cycle on them. When a filter wheel command is given, any wheel which is not moved has its mechanism heated.

Non-global survey TES observations

The bulk of TES Operations activities will involve non-Global Survey observations and activities, even though these produce only about one per cent of the raw data of TES.

There are at least ten volcanoes that TES will want to monitor on a regular basis (this list will change with time). They are Colima (Mexico), Erebus (Antarctica), Etna (Sicily), Fuego (Guatemala), Kilauea (Hawaii), Lascar (Chile), Masaya (Nicaragua), Pacaya (Guatemala), Sakurajima (Japan) and White Island (New Zealand). The plan is to observe each of these volcanoes about 12 times per year, repeat the observation 2, 16, and 18 days later, and revisit each site twice more during the year, with the same observing pattern. Each observation will consist of 212 seconds of data taking, bracketed by 312-second pre- and post-calibrations, for a total of 836 seconds.

There will also be observations of various industrial catastrophes, possibly one per year, with observations repeated 2, 16, and 18 days later.

An Urban/Regional Pollution campaign will involve an estimated 10 events per year, with observations repeated 2 days later. A Regional Biomass Burning campaign will involve an estimated 2 events per year, with observations repeated 2 days later. There will also be a campaign to observe stratospheric effects of volcanic eruptions. One event per year is estimated.

TES also plans to perform two intercomparisons with Aura's HiRDLS instrument per year. TES would be in its Limb mode and be making observations of the same places as HiRDLS at the same time in an attempt to improve both data sets. Each intercomparison is planned for a little less than one orbit.

There are several calibrations planned for the times when the global survey macros are not being executed. They include an estimated two Linearity calibrations per year. Each linearity calibration should take an entire day (3 orbits for cooling down the radiometric calibration source and 8 orbits taking data). There will also be two Gain calibrations per year. These will take several orbits to perform, as the radiometric calibration source needs to be cooled down for these as well. There will be two Global Survey calibration extensions per year. These are long-scan calibrations, to verify that the short-scan calibrations are sufficiently accurate for long scan observations. Each will take a little more than one orbit. Finally, there will be two spatial calibrations per year (lasting well under one orbit).

Table 1. Expected Non-Global Survey TES Observations

Observation Name	**Estimated number of observations per year**	**Duration of one observation macro**	**Scan time per year**	**Calibration time per year**	**Total Data per year**
Volcanology	120	836 seconds	19,200 sec	57,600 sec	331 Gb
Industrial Catastrophe	4	1044 seconds	640 sec	2560 sec	15 Gb
Urban Pollution	20	976 seconds	4080 sec	9600 sec	60 Gb
Biomass burning	4	542 seconds	1088 sec	640 sec	7Gb
Stratrospheric Effects of Volcano	2	541 seconds	5632 sec	3520 sec	41Gb
HiRDLS Inter-comparison	2	4874 seconds	3840 sec	2560 sec	30Gb
Linearity Calibration	2	~11 orbits	N/A	640 sec	3Gb
Gain Calibration	2	~7 orbits	N/A	320 sec	2Gb
Spatial Calibration	2	1144 seconds	N/A	880 sec	5Gb
Global Survey Calibration Extension	2	~7000 seconds	N/A	12,800 sec	58Gb
TOTAL	**160**	**N/A**	**34,480 sec**	**91,120 sec**	**552 Gb**

The planned non-global survey activities are summarized in Table 1. In it, "Duration of one observation macro" refers to the total running time of the macro for a single observation (not for an entire year), including calibrations and Earth observations (not just scan time). "Scan time per year" refers to the total time spent on Earth observation scans in one year (not counting the time between scans). "Calibration time per year" refers to the total time spent on calibration scans in one year (once again not counting the time between scans). "Total Data per year" shows the estimated total data volume, in Gigabits, for the Earth observations and calibrations combined.

As Table 1 shows, there are a total of about 160 observations per year during the time when a global survey is not running and a total data volume of about 552 Gigabits for a year of these observations. This is about a factor of 100 less than the yearly data from the Global Surveys (including calibrations).

Table 1 does not include decontaminations, nor any calibrations that TES might decide to make in coordination with any Aura spacecraft Science maneuver off Earth-point. Nor does it include any further targets of opportunity that may arise. However, these tasks can be time-consuming from an operations standpoint. Decontaminations require changes of states of most TES subsystems, especially of the cryocoolers. Targets of opportunity can be tracked with straightforward and seemingly minor modifications to TES command blocks, however these macro and parameter table changes are in fact changes to flight software that may need to be performed under time pressure.

4. THE TES IOT AND UPLINK OPERATIONS

The TES Instrument Operations team (IOT) consists of two or three people. During launch rehearsals, launch, and the first three months of operations, this team will generally be at GSFC in the EOS Operations Center (EOC). After that, it will operate TES from the Science Computing Facility (SCF) at JPL. While at JPL, the TES IOT interfaces to the GSFC EOC through Instrument Support Terminals (ISTs). TES will have two ISTs. Each IST consists of one Sun workstation and one Windows NT PC. One of the two ISTs will be used primarily for downlink analysis and command verification, while the other will be used for planning and scheduling, and serve as a backup when necessary. The PCs will be used interchangeably for real-time telemetry monitoring, real-time plotting of housekeeping data, and command authorization. The UNIX workstations will support planning, scheduling, and trending of back orbit data.

Uplink Operations begins with long-term planning. The TES Principal Investigator (PI) produces a long-term Instrument Plan once per year, and updates it quarterly. It contains routine operations (the Global Survey), routine in-orbit calibrations, and maintenance activities, as well as special observations which require coordination. Initial scheduling begins about a month before the scheduled activities. A skeleton timeline is generated, and a spacecraft activity schedule is generated from the various instrument long-term plans. The TES Science Team will evaluate this schedule, determine if TES activities need updating. The PI or TES Scientist will submit an activity deviation list if necessary.

The TES IOT begins generating sequence details for unique science activities a week before the start of the week in which the observations are to take place. This includes ground targets for special observations and associated timing. Sequences of commands (macros) for performing Global Surveys, calibrations, and a wide variety of special observations will already be on board, and these only need to be triggered (called) at the proper times. If new targets are needed, this requires changes to these macros or to the macro parameter table or both, which means changing both onboard TES flight software and Aura planning software. The TES IOT presents its timeline for the upcoming special events at weekly meetings. It archives these presentations, along with the command packages that are sent to GSFC and uplinked.

The TES IOT will submit its macro calls, which trigger blocks of onboard commands, to the EOC Flight Operations team (FOT) via the IST. Uplink operations include triggering onboard macros, as well as sending real-time individual commands.

The IOT will check TES constraints and flight rules before saving activities on the timeline of the EOC Master Plan. The FOT will integrate the activities of Aura and its instruments, check Aura mission rules, translate the commands to binary, obtain transmission approval from the individual instrument teams, stuff the data into command packets and transmit the packets to Polar Ground Stations for uplink to the Aura spacecraft. An EOC uplink is called a Master Command Loads (MCL). These loads are sent daily, about 31 hours before the start of the day on which they become valid. Two loads are onboard the spacecraft at a time, namely the one that is executing and the one for the following day. Late changes to the following day's Master Command Load can be made in an uplink. This permits validation of the load after it is received by the spacecraft, and allows GSFC to send late changes as little as 7 hours prior to the start of the day in which they are to be executed.

MCL packets are stored in a buffer unit by Aura until they are ready for use. At this point, they are forwarded to TES over a 1553B interface. TES flight software receives the packets, validates that the CCSDS headers are compliant, and validates the TES commands inside the instrument data field. It then handles and executes the sequentially loaded commands according to command type.

In addition to uplinking instrument commands, the GSFC FOT needs to maintain an up-to-date onboard ephemeris. The GSFC Flight Dynamics Facility (FDF) provides GSFC with a daily ephemeris load. This load consists of 289 sets of position and velocity vectors, spaced 10 minutes apart. While this adds up to 48 hours of information, only the first 24 hours of each load are nominally used since the last 24 hours will be overwritten by the time they are to be used. Accurate ephemeris data is critical for TES, as a TES nadir pixel is only 530 meters along the flight path.

The GSFC FDF also prepares orbit maintenance maneuvers. These maneuvers are performed to make up for drag and to adjust inclination. The main driver for these maneuvers is the maintenance of a +/- 20-kilometer ground track repeat cycle (every 16 days). These maneuvers are performed every 2 to 24 weeks, depending upon the solar effects on spacecraft drag, and the TES IOT needs to be aware of the schedule for these and any other maneuvers if only to avoid conflicts with the Global Survey.

5. TES Engineering Data

TES Low-rate Engineering Data

TES data is provided to the TES IOT in packets identified by packet IDs (called "application IDs" or APIDs). Low-rate engineering data will be viewed near real-time through the ISTs. Each low rate packet is 256 bytes, with an instrument data field of 241 bytes, and is generated once every 4 seconds. Table 2 shows the structure of the nominal engineering data packet.

Table 2. TES Low-Rate Nominal Engineering Data Packet Structure

Low Rate Nominal Engineering Data Packet	256Bytes
Packet ID Field	2 Bytes
Packet Sequence Control Field	2 Bytes
Packet Length Field	2 Bytes
Secondary Header Field	9 Bytes
Instrument Data Field	241 Bytes
Command and Data Handling Subsystem Data Set	48 Bytes
Calibration Subsystem Data Set	24 Bytes
Focal Plane Cooler A Subsystem Data Set	38 Bytes
Focal Plane Cooler B Subsystem Data Set	38 Bytes
Focal Plane Subsystem Data Set	13 Bytes
Interferometer Control Subsystem Data Set	1 Byte
Laser Subsystem Data Set	16 Bytes
Mechanical Subsystem Data Set	30 Bytes
Pointing Control Subsystem Data Set	15 Bytes
Power Subsystem Data Set	8 Bytes
Filler Data	10 Bytes

This Low-rate Nominal Engineering Data Packet is also referred to as the Housekeeping Data Packet.

The above data are used by the TES IOT to assess the health and safety of TES. The TES IOT, when at JPL, is nominally present only during normal working hours, however the GSFC FOT monitors the health of Aura and its instruments around the clock, and will notify whichever

IOT member happens to be on call should an anomaly occur.

In addition to the Housekeeping packets, there are three other types of low rate packets. These special data packets can be requested by command, and are then transmitted in place of one or more housekeeping packets. These packets contain special cooler data, bit error status indicators, and register data.

Use of the High Rate Data Stream by the TES IOT

The TES IOT also has access to information contained in the High Rate Science data that gets sent to the LaRC DAAC.

Processing of the Global Survey, Special Observations, and Calibration data are the responsibility of the SIPS. The high rate science packets also contain engineering measurements ("embedded data"). These data are required by the Science team as well as by the IOT. Although these data are present in nominal low rate packets, having them in the high rate data provides a useful backup.

Dump data, which is received only in high rate packets are of use only to the IOT, and is needed to confirm the success of memory loads, macro loads, and table loads. These data can be requested from the Langley DAAC and must then be processed by the IOT. These will not be made available in low rate telemetry because of the downlink rate. Dump data will be requested as expedited packets which arrive in 3-4 hours as opposed to a nominal wait of 24 hours.

The requirements on the IOT to use high-rate data mean that it must capture some of the high-rate data from the Langley DAAC. Any delays caused by hardware or software problems in accessing DAAC data then affect the ability of TES to receive dump data and possibly some of its performance data.

Relationship of Science Data and Engineering Data

As we have seen, Science data are normally used to obtain geophysical parameters and to determine their quality and calibrate them. Under some circumstances, however, these data are germane to the health and safety of TES. If radiances appeared far off from expected values, one might suspect a PCS anomaly, and recheck PCS encoder outputs. A variety of suspicious spectra could in theory be observed, with anomalous lines, "ghosting," or mere inconsistency with spectra based on ground observations, and these would again raise doubts about one or more TES subsystems. Asymmetry of interferograms would raise questions about the ICS. The TES IOT needs to be aware of possible engineering and operations ramifications posed by anomalous Science data.

The clearest example of Science data determining an engineering response is in the area of contamination. TES optics are susceptible to contamination from water vapor, carbon dioxide, and a variety of organic compounds. The result of such contamination will be to reduce the system Signal-to Noise ratio and to impose unwanted absorption features onto the spectra. When the signal from calibration sources declines by 5%, or when unacceptable absorptions due to specific contaminants are noted, the Science Team will request a TES decontamination. In Decontamination submode, TES will be outgassed by permitting it to be warmed up to spacecraft ambient or higher, with the calibration sources on and the cryocoolers off. The TES IOT will follow trends in signal performance so that it can anticipate when the next decontamination needs to be scheduled.

A variety of engineering measurements can yield parameters under certain conditions that will cast doubt on the quality of Science data taken at that time. Detector temperatures are a good example of these.

6. TES Anomaly Planning

The FOT or IOT may observe a TES anomaly. If the FOT observes a TES anomaly, the PI and the IOT member on call will be notified; if the IOT observes the anomaly, it will notify the PI and the FOT. In response to an anomaly, low rate engineering data are pulled in, some special low-rate data may be requested, and a team is formed to resolve the anomaly. Anomaly resolution generally involves several steps: making sure the instrument is in a safe state, obtaining all the data for analyzing the problem, establishing an accurate timing of the anomaly, identifying a single root cause, validating the plausible cause, determining the appropriate corrective action or workaround, and carrying it out.

Actions that must be taken immediately are generally performed using Fault Protection responses. The IOT produces the command macros for these responses. These macros are stored on the spacecraft and executed autonomously when triggered necessary. A set of Fault Protection monitoring routines checks for out-of-limit conditions. If such a condition is met for a sufficient number of consecutive measurements, a Fault Protection response is triggered.

Contingency Responses

There are several situations in which a contingency response may be desired. Contingency responses are triggered from the ground upon request, as opposed to Fault

Protection responses, which are autonomous. During activation or some other critical activity, the Ground may be called upon to perform an immediate action in the event of a fault, and will have one or more contingency responses available for immediate use. One possible example might be to trigger commands to release the ICS latch immediately should the Earth shade open anomalously and prematurely. Contingency responses can also be used when an important command is included in a stored sequence. Should the sequence be halted for some reason, the command can then still be sent real-time. TES has a "safe" mode which it can retreat to autonomously via TES Fault Protection in the event of a variety of anomalies. However, this mode precludes data-taking, thus contingency commands to "recover from Safing" are needed in case the cause of a Safing is known (possibly due to repeated experiences with it). Contingency commands can also be used to pre-empt a Fault Protection response, if it is clear from data trends that a response limit will be reached.

A final example of contingency commands are "go" and "no-go" commands. These are used as part of a strategy for avoiding unsafe states that might be reached were an anomaly to prevent the execution of a stored command. The "go" strategy entails having flags control the execution of timed commands that have certain prerequisites for being safe to issue. When it is seen in telemetry that it is safe to issue the commands, real-time ground commands are issued to permit their execution. The "no-go" strategy uses flags as before, but issues ground commands only if it is not safe to proceed. This strategy will backfire if, for some reason, the "no-go" command does not reach Aura.

Effect of Ground System anomalies on TES Operations

The effect of Aura missing a single downlink pass is significant. While there is enough room in the Aura buffer to hold two orbits worth of data, in the worst case, some data can be lost. The reason is that on the next pass, Aura may be unable to download all two orbits worth of data, and by the time it can catch up, some data could be overwritten. Missing two or more consecutive passes loses data at once.

Bit errors, whether produced in the instrument, in transmission, or on the ground, are a potential problem. A Fourier Transform Spectrometer is particularly susceptible to data errors because every interferogram sample contributes to every spectral amplitude. Bit errors near the point at which the optical path difference is zero are the most severe.

Even a bit-error rate of one in 100,000 would be hopeless for TES, since a typical interferogram of 256 kilosamples, digitized at 14 bits per sample, is over 3 million bits, which would mean an average of 30 errors in each interferogram. To meet the TES requirement of having no more than 1% of its interferograms irretrievably corrupted by data transmission errors, Reed-Solomon encoding is used to reduce such error rates. In general, bit errors are non-random, and occur at the time of solar storms, or over the poles, or over the South Atlantic Anomaly (SAA), which is a large area centered near Rio de Janeiro.

It is unlikely that TES will ever require a prompt ground command to survive. An exception may be when Aura is in survival mode, where the ability to uplink commands quickly may affect TES's ability to recover.

7. RESOLUTION OF TES OPERATIONS ISSUES

The completion of preliminary versions of the principal TES macros over three years prior to launch has permitted the consideration of options to modify the TES command features provided by flight software. This has resulted in less complex TES command macros and has added flexibility to TES operations. The following are examples of some of the TES operations issues in which additional options could be considered due to the early date at which they were addressed.

Macro Parameter Table

The issue was whether or not to include a parameter table that would include observation type, target position, filter wheel positions, and signal chain gains.

There were several advantages in having such a table that offset the work of generating, maintaining, and accomodating it. The same macro could then be used for a number of different applications and targets, with the only changes being in the parameter table. In fact, a call to a macro could specify a starting line in the parameter table, so that one could use the same macro for different preplanned targets without changing either the macro or the table. A third advantage was coupled to the addition of a command that would permit switching to a new line on the parameter table based upon a parameter in the table itself. This command, together with the table, resulted in a significant simplification of the TES macros. For example, the Global Survey, without the table, needed nine macros and a total of over 200 commands. Using 12 lines of the parameter table reduced this to three macros and 76 commands. Similar improvements were made with the special science macros.

All-Purpose Macro

The issue was whether or not to anticipate changes in observation strategies by designing and testing a "all-pupose" macro that could be adapted to suit any set of filters and scans. This issue was raised early enough so that the flight software team would have been able to create the branching instructions necessary to produce such a macro. In fact, the all-purpose macro was rejected because the modifications required to use it would have resulted in nearly as much work as the production of a new and specialized macro. Furthermore, a major aspect of using timed stored sequences is the ability to know the exact time at which each command will execute. Branch commands would violate that principle. In addition, creating and testing such commands would have used flight software and integration resources.

Resuming the Global Survey

Initially, the plan was for a Global Survey to last 4 days, with 2 orbits of pre-calibration, 58 orbits of data-taking, and 2 orbits of post-calibration. With this plan, it would be advantageous to be able to resume a survey that had been interrupted by a planned spacecraft maneuver or by a minor, quickly resolved anomaly. Once again, this issue was considered early enough so that Flight Software could have prepared a command to resume the Survey. A resumed survey would have ended at the original planned completion time. However, the reduction in the length of the Global Survey to 16 orbits removed the need for this command.

Use of "Wait" command for Go and No-Go Strategies

Commands within macros execute at specified relative times from the previous command. However, there is a command to wait until a specific event occurs before executing the next command. This "Wait" command will used to start a Global Survey or Science Sequence when the South Pole Apex is crossed or when a target is reached. However, the wait command, given a timeout, can be used to halt a sequence if a flag permitting its further execution is not set. This additional feature can support the use of a "Go" strategy during TES activation.

Modification of Critical Commands

A critical activity, such as releasing the Earthshade latch or Translator latch, is not allowed to be performed on the basis of a single command. At least two separate commands are required. This raised the issue of whether the commands ought to perform distinct and separate hardware tasks. A second issue was how to handle the failure of a critical command. By having separate commands to handle the closing of different circuits, both problems could have been resolved in command blocks. However, a flight software resolution was more straightforward for both issues and is being implemented.

Modification of Nominal Commands

Commands to control background heating to the filter wheel mechanisms are required for any TES observation, to comply with the constraint against heating the wheel mechanisms during data-taking. This raised the issue of whether the heating control command could be used to perform an additional task. The command was then expanded to support filter wheel lubrication.

Synchronization of Mechanisms for data-taking

The Global Survey macro is barely able to squeeze the seven required scans into its 81.2-second allotment. To do so, the PCS and filter wheels need to move while the translator is ramping up and down between scans. This raised several questions: how quickly would the translator come up to speed after a scan command, how fast could the filter wheel move to the next position, and how quickly could the PCS move to its next position?

At first, it appeared that 0.8 seconds would be available for moving the filter wheel in the Global Survey. The filters were and macros were arranged so that a filter wheel would never have to move more than one position at a time. On further reflection, after tests on the ICS, it became clear that there were only 0.7 seconds available between some of the scans when one could be sure that no data was being taken. Flight software now allows the speed at which the filter wheel moves to be modifiable in flight, and this speed will now be set initially so that a wheel will move one position in less than 0.7 seconds.

The required elapsed times for moving the PCS gimbal were derived so that they would be consistent with the 81.2-second sequence. However, these times would have resulted in a significant loss of data when TES needed short PCS gimbal moves to support its ability to stare at a specific target in special science observations. As a result, the table of times for moving the PCS gimbal is being modified to support such activities without an unnecessary loss in performance.

Strategy for Dealing with Invalid Commands

Before TES commands and command blocks can be executed, they must have been tested on the ground, checked by the IOT for compliance with flight rules, checked by command scripts to execute, checked by the Ground System, and checked by the FOT. In addition, flight software prevents some invalid commands from executing (by checking the TES submode). Thus, invalid commands should be rare. They can be rejected outright.

A command to move a TES mechanism that is already in use is invalid, and one option would have been to buffer some of these commands and try to execute them later. But due to the complexity of such a task and the presumed lack of benefit for such an approach, this option was rejected. When a command is rejected, an "invalid command" counter will be incremented, the macro issuing the command will be halted autonomously, and TES will be placed in its "safe" submode.

Submodes and Submode Transitions

There were two issues here: what operational submodes were needed on TES, and what macros should be used to transition between submodes?

Four submodes were deemed necessary due to the anticipated enforcement of flight rules in flight software: Mission, Decontamination, Safe, and Engineering. The

Mission submode is for data-taking, and commands to perform data-taking scans will be rejected unless TES is in Mission submode. Commands to turn on the decontamination heaters will be rejected unless TES is in Decontamination submode. The Safe submode can reached autonomously via Fault Protection, or by Ground Commands when TES is best off in a protected state. The Engineering submode is used to perform transitions between the other submodes. Commands to turn on the cryocoolers will be rejected unless TES is in Engineering Submode.

The second issue was whether or not a command to go to Mission, Engineering, or Decontamination submode should perform the necessary state changes on TES to place it in that submode. This option was rejected, since submode transitions into and out of Decontamination are complex, and it is undesirable to have them triggered by a single command. As a result, the TES IOT will simply check low-rate telemetry to verify that TES is in the proper state and then issue a ground command to set the TES submode.

Commanding Targets of Opportunity

While the observation of targets of opportunity may produce only a small portion the total data from TES, they will be labor-intensive for the IOT. The Ground system provides reports to the IOT showing when targets are in the TES field of view. The TES IOT needs such a report for targets of opportunity as well, so such targets need to be added (at least in effect) to the Ground system data base. For TES to observe such targets the IOT will have to modify the onboard TES macro parameter input table. This table will have several hundred lines, and the entire table will need to be reloaded. It is possible that a TES macro will need to be modified as well. These are flight software changes. These tasks will need to be performed quickly, and need to be coordinated with all other planned TES and Aura activities. This raised the issue of whether a command could be created to modify a line of the macro parameter input table. However, reloading the table appears to be the best option.

Limited Bandwidth for Uplink

Uplink packets on Aura are 32 words. Four are needed for the CCSDS header, so only 28 remain for a TES command. This is sufficient for all TES commands except a variety of load commands: macro loads, memory loads, and table loads. The memory loads include cryocooler subsystem memory loads and patches. These commands include the contents of the loads, so they often exceed the 28-word (27 words for cryocooler commands) limit. This issue was brought up early enough so that Aura agreed to segment these commands into multiple packets.

The entire strategy of having a large set of onboard macros originated as a response to the limited uplink bandwidth. As a result, most of the TES contributions to the Aura Master Command Load will be triggers for (calls to) onboard macros.

Limited Bandwidth for Engineering Downlink

The low-rate packet size of 256 bytes and the transmission rate of one packet every four seconds posed two issues for TES operations: how would TES obtain dumps of its tables, macros, and memory, and how would TES obtain important but infrequently-needed cryocooler data?

As this paper has shown, the resolutions of these issues were dissimilar. In the case of cryocooler data, as well as VME register and TMR status data, special low-rate packets were created that would have higher priority than the nominal low-rate packets. The loss of nominal low-rate packet data while these special packets were downlinked was considered acceptable. Furthermore, much of the nominal low-rate data are available in embedded high rate data as a backup.

However, it was inconvenient to downlink a large memory dump in low-rate data, so it was decided to acquire dump data via the high-rate data stream.

8. CONCLUSIONS

This paper has described the TES instrument from an Operations perspective. Global Survey TES Operations tasks are not unusual for a space-borne Science instrument. Even new and unplanned tasks decided upon once in orbit are likely to be highly similar to those which have already been planned and tested. The most involved tasks (submode changes, new targets, and flight software loads) are part of nominal planning. However, it is precisely in nominal operations a great deal of operational complexity resides. The articulated mirror, high duty cycle, need for explicit coordination between subsystem commands, need to respond quickly to targets of opportunity, variety of flight rules, the intricate activation process, and the need to monitor the high-rate data stream make TES a challenging instrument to operate. Generation of the TES command blocks early in the design process has enabled the consideration and implementation of innovative resolutions to a variety of operational issues.

Acknowledgements

The authors would like to thank the TES Project Manager, Tom Glavich, TES Principle Investigator Reinhard Beer, and TES Algorithm Lead Helen Worden for their helpful suggestions about the first draft of this paper. We thank Ed Miller, the TES Instrument Manager, for his review of the paper and for supplying us with the TES Block Diagram. And we thank Angelita Kelly of GSFC for the diagram of the TES Flight Operations architecture.

REFERENCES

[1] Reinhard Beer, *Remote Sensing by Fourier Transform Spectroscopy*, John Wiley and Sons, New York, 1992

[2] Reinhard Beer, "Tropospheric Emission Spectrometer Scientific Objectives & Approach, Goals & Requirements," *JPL D-11294 Revision 6.0*, April 1999

[3] Daryl G. Boden and Wiley J. Larson, *Cost-Effective Space Mission Operations*, McGraw Hill, New York, 1996

[4] Tom Glavich, "Tropospheric Emission Spectrometer Experiment Implementation Plan," *JPL D-13017 Rev A*, March 1999

[5] Steve Larson, "Tropospheric Emission Spectrometer Ground System Operations Concept," *JPL D-18451 Version 1.0*, September 2000

[6] Norman Lee, "Tropospheric Emission Spectrometer Command and Telemetry Handbook," *JPL D-15388, Version 3.0*, June, 2000

[7] Norman Lee, "Tropospheric Emission Spectrometer System Fault Protection Requirements and Algorithms," *JPL D-17782, Preliminary Release*, May, 1999

[8] E. Miller, W. S. King, R. Steinkraus, K. English, N.Nerheim, M. Brenner, J. Rodriguez, S. Collins, C. Bruce, R. Holm, L. Robinson, M. White, and S. Gunter, "Tropospheric Emission Spectrometer System Detail Design Specifications and Requirements," *JPL D-18085 Version 1.0*, September 1999

[9] Steven Tyler, "Tropospheric Emission Spectrometer Flight Operations Requirements and Plan," *JPL D-17848 Version 1.0*, May, 1999